In an adaptive optics based large-aperture space telescope 11, as illustrative in Fig. 1, light from a nominal point source above the atmosphere enters the primary mirror 13 of the telescope 11 and is focused and directed by mirrors 14A and 14B to an adaptive optics subsystem 15. The adaptive optics subsystem 15 includes a tilt mirror 17 and a deformable mirror 19 disposed between its source (the mirrors 14A and 14B) and an imaging camera 31 and capturing an image of the point source. A beam splitter 21 directs a portion of the light directed to the imaging camera by the mirrors 17, 19, to a wavefront sensor 23 that measures the phase distortion in the wavefronts of light directed thereto. A computer 25 cooperates with mirror driver 27A to control the tilt mirror 17 to stabilize the image, and cooperates with the mirror driver 27B to control the deformable mirror 19 to compensate for the phase distortions measured ~~therein~~ in the wavefront of the incident light forming the image, thereby restoring sharpness of the image ~~sharpness~~ lost to atmospheric turbulence. In recent years, the technology and practice of adaptive optics have become well-known in the astronomical community.

On Page 3, amend the fourth paragraph as follows:

Thus, there is a great need in the art for an improved wavefront sensing mechanism that ~~avoid~~ avoids the shortcomings and drawbacks of prior art Schack-Hartmann wavefront ~~sensor~~ sensors.

On Page 5, amend the last paragraph as follows:

Fig. 8A shows a dispersed spot image captured by the imaging device of the wavefront sensor of the present invention, and having a phase difference of 0.0 μ.

On Page 6, amend the first through sixth paragraphs as follows:

Fig. 8B shows a dispersed spot image captured by the imaging device of the wavefront sensor of the present invention, and having a phase difference of 0.1 μ.

Fig. 8C shows a dispersed spot image captured by the imaging device of the wavefront sensor of the present invention, and having a phase difference of 0.3 μ.

Fig. 8D shows a dispersed spot image captured by the imaging device of the wavefront sensor of the present invention, and having a phase difference of 0.5 μ.

Fig. 8E shows a dispersed spot image captured by the imaging device of the wavefront sensor of the present invention, and having a phase difference of 1.0 μ.

Fig. 8F shows a dispersed spot image captured by the imaging device of the wavefront sensor of the present invention, and having a phase difference of 3.0 μ.

Fig. 9 shows the intensity values of a slice (along the dispersion direction) through a dispersed spot image captured by the imaging device of the wavefront sensor of the present invention.

On Page 7, amend the second through fourth paragraphs as follows:

Referring to the figures in the accompanying Drawings, the preferred embodiments of the ~~Planar Laser Illumination and (Electronic) Imaging (PLIIM) System of the~~ present invention will now be described in great detail, wherein like elements will be indicated using like reference numerals.

As shown in Fig. 2, light from a nominal point source above the atmosphere enters the primary mirror 113 of the telescope 111 and is focused and directed by mirrors 114A and 114B to an adaptive optics subsystem 115. The adaptive optics subsystem 115 includes a tilt mirror 117, ~~and~~ a deformable mirror 19 disposed between its source (the mirrors 114A and 114B), and also an electronic imaging camera 131 for capturing an image of the nominal point source. A beam splitter 121 directs a portion of the light directed to the imaging camera by the mirrors 117, 119 to a wavefront sensor 123 that measures the phase distortion in the wavefronts of light directed thereto using the novel wavefront sensing method of the present invention. A computer 125 cooperates with mirror driver 127A to control the tilt mirror 117 to stabilize the image of the point source, and cooperates with the mirror driver 127B to control the deformable mirror 119 so as to compensate for and correcting large phase distortions measured therein, substantially free of the 2π phase resolution ambiguity associated with prior art wavefront sensing techniques ~~known in the art~~.

Long-baseline optical interferometers utilize a well known dispersed fringe technique (see, for example, Applied Optics vol. 35, #16, p. 3002). In the dispersed fringe system, the beams from two telescope apertures are combined in the pupil plane and brought to a common

focus. If the path lengths from the two apertures are closely matched, there will be interference between the two beams and fringes will be formed. For any given wavelength, this fringe pattern shifts with changing path difference but the pattern repeats for every one wavelength change in path. This is known as a 2π phase resolution ambiguity. If this focal spot is spectrally dispersed, then the fringe pattern as a function of wavelength may be recorded. Since the ambiguity in path difference is one wavelength at the measurement wavelength, by measuring at multiple wavelengths, it is possible to extend the unambiguous path difference measurement range very significantly.

On Page 8, amend the first and third paragraphs as follows:

According to the principles of the present invention, the wavefront sensing method employed in adaptive optics subsystem 115 generally comprises: using each subaperture of modified Hartmann sensor 123 to spatially sample incident light from the input beam and form a (far-field) dispersed spot image with a fringe pattern corresponding to each sample of incident light; and using an image camera ~~131~~ 124 as part of sensor 123 to capture the image of the dispersed fringe pattern and an associated image processor 125 to ~~capture and~~ analyze spectral components of the dispersed fringe pattern in order to derive a measure of the local phase distortion in each sample of incident light, in a way which is substantially free of the 2π phase error ambiguity characteristic of prior art wavefront sensing techniques.

Referring to Fig. 5, the optical components comprising an exemplary wavefront sensor according to the present invention are schematically illustrated. The wavefront sensor ~~100~~ ~~includes~~ comprises optical elements 117 that spatially sample incident light and form dispersed spots with a fringe pattern corresponding to samples of the incident light. ~~An~~ As shown, wavefront sensor 123 further comprises electronic imaging device 124 (e.g., CCD camera) ~~records~~ for recording the light transmitted through the optical elements 1503 to capture an image of the fringe pattern of such spots. The pupil plane is shown at 126. ~~An~~ The wavefront sensor 123 further comprises image processor 127 ~~analyzes~~ for analyzing spectral components of the fringe pattern in the image captured by the imaging device 124 so as to derive a measure (that eliminates the 2π ambiguity) of the local phase distortions in the samples of incident light.

On Page 9, amend the first full paragraph as follows:

Alternatively, the optical elements 117 of the wavefront sensor ~~100~~ 123 of Fig. 5 may comprise one or more refractive optical elements (such as prisms) or one or more diffractive optical elements (such as a diffraction grating or hologram) or a combination of the two, e.g., a grism. A grism, or Carpenter prism, whose function is schematically illustrated in Fig. 4C, is a transmission grating mounted on a prism that together act to disperse incident light (along a predetermined dispersion direction) without deviating a component (its design wavelength) of the incident light. It is preferable that the optical elements 117 provide an independent dispersive direction (which is preferably aligned along the direction of the phase step to be measure) for each subaperture. Holographic gratings or an array of grism elements provide such independent dispersion directions. Optical elements with a singular dispersive direction may be used, but this complicates the analysis for phase steps that ran at an angle relative to the singular dispersion direction.

On Page 10, amend the second and fourth paragraphs as follows:

As illustrated in Fig. 5, the wavefront sensor ~~1~~ 123 of the present invention includes ~~an~~ imaging device 124 (e.g., CCD camera or CMOS camera) that captures an image of the fringe pattern distributed along the dispersion direction by the dispersive elements 117, and ~~an~~ image processing device 127 that analyzes the spectral components of the fringe pattern to derive a measure (that eliminates the 2π ambiguity) of the local phase distortion in the corresponding sample of incident light. Preferably, the image processing device 127 analyzes the spatial frequency of the spectral components of the fringe pattern to derive a measure (that eliminates the 2π ambiguity) of the local phase distortion in the corresponding sample of incident light. Fig. 12 illustrates exemplary operations of the image processing device in analyzing the spatial frequency of the spectral components of the fringe pattern to derive a measure (that eliminates the 2π ambiguity) of the local phase distortion in the corresponding sample of incident light.

The wavefront sensor of the present invention 123 shown in Figs 2 through 5 and as described above is preferably operated in two modes. The first mode of operation is used when the estimated phase step error is large (e.g., greater than 1/2 wave), and provides a coarse

measure of phase distortion without ambiguity (e.g., the 2π ambiguity is resolved). The second mode of operation is used when the phase step is small (e.g., less than 1/2 wave), and provides a finer measure of such phase distortion. In the first mode of operation, slices (along the direction of dispersion) in the image of the fringe pattern are analyzed to yield an estimate of the phase error. This estimate is used to correct the error until the size of the step is reduced below 1/2 wave. At this point, the second mode of operation is used. In the second mode of operation, slices (perpendicular to the direction of dispersion) of the image of the fringe pattern are analyzed to the measure the phase error with greater accuracy, which is used to further reduce the phase step error. Simulations indicate that measurement of phase step errors of less than 1/50 wave should be possible. This one sensor then combines both the coarse and fine phase measurement capability in one monolithic optical instrument.

On Page 11, amend the first and second full paragraphs as follows:

Figs. 12A and 12B illustrate a more detailed description of exemplary operations of the wavefront sensor of the present invention 123 in performing both coarse and fine phase measurement for a given subaperture. In step 1201, the optical elements that form the far-field fringe pattern for a given subaperture (e.g., dispersion element) are aligned such that dispersion occurs primarily in a direction parallel to the edge of a potential phase step. In step 1203, the imaging device 124 captures an image of the fringe pattern (which corresponds to the spectral components of the dispersed far-field spot) for the given aperture. Optionally, image processor 127 may apply image processing techniques (such as filtering, contrast enhancement, etc) to improve the signal-to-noise ratio of the interference fringe therein.

In step 1205, the image processor 127 calculates a two-dimensional gradient of the image produced in step 1203 and derives slope of the fringe pattern from the gradient values. This slope provides the sign of the course estimate of phase step error as derived in step 1217.

On Page 12, amend the fifth and sixth paragraphs as follows:

In step 1225, the image processor 127 identifies the location of the centroid of the fringe pattern within the slice. In step 1227, the image processor 127 calculates deviation of the

centroid (calculated in step 1225) from location of a geometric null (e.g., location of a reference centroid measured by the same analysis of the fringe pattern from a reference source). This deviation provides a measure of the phase error for a given spectral component (wavelength) as a function of the wavelength of the spectral component. In step 1229, the wavelength corresponding to the phase error measured in step 1227 is identified, and this wavelength is used to convert such phase error to an absolute phase error value for the given spectral component This operation involves mapping the pixel coordinates of the slice to a wavelength. Such mapping is preferably accomplished in a calibration phase, whereby the wavefront sensor 123 is illuminated with a source with predetermined spectral components. The image ~~device~~ processor 127 identifies such predetermined spectral components in its image plane (pixel coordinates), determines a mapping between pixel coordinates and wavelength, and stores such mapping in persistent storage for subsequent use.

After the loop ends in step 1231, the operation continues in step 1233 wherein the image processor 127 derives a fine phase step error from the absolute phase errors (step 1229) for the slices, for example, by averaging the absolute phase errors.

On Page 13, amend the first through third paragraphs as follows:

In step 1235, the image processor 127 outputs the fine phase step error to a mirror correction routine that corrects for the fine phase step error, and returns to the first mode of operation in step 1203.

The wavefront sensor of the present invention 123 as described above is preferably used as part of an adaptive optic system as illustrated in Fig. 2. The wavefront sensor 123 measures the phase distortion in the wavefronts of light directed thereto, and operates in conjunction with a computer 125 and mirror drivers to control one or more mirrors (such as tilt mirror 117 and deformable mirror 119 to compensate for the phase distortions (i.e. errors) measured therein.

Fig. 10 illustrates an exemplary embodiment of an adaptive optic system according to the present invention. It provides a schematic view that shows the geometric arrangement of the apertures of the wavefront sensor overlaid onto the segments of a multi-segmented deformable mirror. The bottom layer represents the segments of the deformable mirror. As shown there are seven large hexagons ~~1000~~ 1100, with six large hexagons arranged around the seventh, each of

which is a mirror, or mirror segment. We use the term "mirror" to refer to the overall surface that is composed of individual "mirror segments." Here it is assumed that the mirror to be phased consists of hexagonal segments, although other shapes also work. The top layer 250 represent the apertures of the wavefront sensor 123. As shown there are nineteen (19) subapertures, each of which is hexagonal in shape. There are two types of subapertures shown here. A first type of apertures 1115 (referred to as "dispersed Hartmann apertures") 1115 form far-field spots corresponding to samples of the incident light and disperse the fringe pattern of such spots as discussed above. A second type of apertures 1110 (referred to "normal Hartmann aperture") do not perform dispersion. Arranged around the six edges of the center mirror segment are six dispersed Hartmann apertures 1115 ~~as~~ that are used to measure the piston difference to adjacent mirror segments from the center mirror segment. Additional dispersed Hartmann subapertures 1115 are located between the centers of the other mirror segments. In the center of each mirror segment is a normal Hartmann subaperture 1110 used to measure the tilt of the segment. This single subaperture may be replaced by many smaller subapertures if the segment requires figure measurement or control. This hybrid optical element would preferably be fabricated as a single unit with holographic gratings and refractive lenslets. It could be mounted in a retractable holder in a pupil plane of the telescope system. The resulting images would be ~~collected with~~ captured by imaging camera 131.

On Page 14, amend the first and second paragraphs as follows:

Fig. 13 illustrates an exemplary mirror correction scheme utilized by the adaptive optic system of Fig. 10 to control displacement of the mirror segments to correct for the phase errors provided by wavefront sensing operations. In step 1301, a loop is performed over one or more of the mirror segments of Fig. 10. Step 1305 is performed for each given segment in the loop. In step 1305, the estimated phase step errors produced by the wavefront sensor 123 that correspond to the given segment (including those phase step errors corresponding to its edges) are used to construct a phase error for the given mirror segment in a global coordinate system of the deformable mirror. The loop ends in step 1303 and operations continue to step 1307 wherein the phase error of the mirror segment(s) calculated in step 1305, which are represented in the global

coordinate system of the deformable mirror, is used to derive segment displacements that best corrects for such phase error (i.e., forms the complex conjugate of such phase errors).

In addition, the improved wavefront sensor 123 and adaptive optic subsystem as described above is preferably used as part of a large aperture space telescope as illustrated in Fig. 2. Because of the large dynamic range of the wavefront sensor and its ability to perform wavefront measurement without ambiguity, it is ideally suited to performed course adjustment of a large aperture space telescope to thereby correct for large phase steps that are initially present within such systems.